7. NATURALLY OCCURRING AND ACCELERATOR-PRODUCED RADIOACTIVE MATERIAL

7.1 INTRODUCTION

Naturally occurring and accelerator-produced radioactive material (NARM) is a broad category that includes accelerator-produced radioactive material and naturally occurring radioactive material (NORM) and is not source, special nuclear, or by-product material. Accelerator-produced radioactive materials (the "A" in NARM) include wastes generated by accelerators used in subatomic particle physics research.

The term NORM refers to materials not covered under the AEA whose radioactivity has been enhanced (i.e., materials whose radionuclide concentrations are either increased or redistributed compared to typical background levels either naturally or as the result of human intervention or processes). Examples are exploration and production wastes from the oil and natural gas industries and phosphate slag piles from the phosphate mining industry. NORM is not used to describe or discuss the natural radioactivity of rocks and soils or background radiation.

NARM wastes are currently not regulated by any federal agency. Responsibility for regulating the disposal of NARM is not addressed in the Atomic Energy Act (AEA).[1] Regulation of NARM disposal currently rests with the states as part of their authority for ensuring the protection of public health and safety.[2,3] However, currently a few states do not have regulatory programs for NARM wastes. Table 7.1 (data from refs. 4 and 5) summarizes the current status of state regulations for NORM wastes.

7.2 WASTE CHARACTERIZATION

As described in ref. 6, accelerator-produced materials are generated in small quantities and are comprised of radionuclides with short half-lives. Table 7.2 (data from ref. 7) lists the radionuclides found in accelerator-produced radioactive materials. Except for ^{81}Kr, ^{145}Pm, and ^{22}Na, most of these radionuclides have short half-lives that are measured in days, hours, or minutes. Accelerator wastes include accelerator targets, wastes from accelerator maintenance and D&D, and wastes from radiopharmaceutical manufacture. Because accelerator-produced material is caused by the bombardment of radiation, it has the same properties as material that is regulated by the Atomic Energy Act (AEA) and is, therefore, typically handled in the same regulatory manner as AEA material. Because of its usually short half-life, accelerator-produced material can often be stored until it has decayed to insignificant levels. However, it is not clear whether this approach will work for the possibly large volumes of such materials that may result from the future decommissioning of large accelerator facilities.

Compared to radioactive wastes associated with most research, industrial, and medical applications, NARM wastes have low radioactivity concentrations. NARM wastes with more than 2 nCi/g of ^{226}Ra or equivalent are commonly referred to as discrete NARM waste; below this threshold, the waste is referred to as diffuse NARM waste.

NORM wastes, which exclude accelerator-produced radioactive materials, result from concentrations of naturally occurring radionuclides found in the earth's crust. Table 7.3 summarizes the major characteristics of all the naturally occurring radionuclides identified in the *Chart of the Nuclides* (ref. 8).

7.2.1 Discrete Wastes

Discrete wastes have a relatively small volume but large radioactivity; these include industrial gauges, old radium watch and industrial dials, radium needles in medical equipment, and resins (filters) that remove radioactive radium and other NORM from ground water.

7.2.2 Diffuse Wastes

Diffuse wastes are characterized by a relatively large volume with small radioactivity.[9] These materials result from industrial processes and include:

- coal ash and slag from utility electrical generation;
- solid wastes from geothermal energy production;
- slag, leachate, and tailings from the mining and processing of metals other than uranium or thorium (e.g., copper);
- sludge from drinking-water treatment;
- scale, sludge, produced water, and equipment from oil and natural-gas production containing NORM; and
- wastes (phosphogypsum and slag) from mining phosphate ores for fertilizer (ammonium phosphate) production.

A summary of domestic processes that generate NORM wastes are given in Table 7.4 (based on refs. 10–13). Levels of specific activity for these wastes typically vary from 2–200 pCi/g.[10,14] Table 7.5 (adapted from refs. 13 and 15) lists major radionuclides found in diffuse NORM wastes. Estimated radionuclide concentrations reported by the Environmental Protection Agency (EPA) in ref. 13 for each diffuse NORM category are provided in Tables 7.6–7.11.

Descriptions of the specific characteristics of diffuse NORM wastes are given in the following and are based on the EPA waste characterization and preliminary risk assessment study of ref. 13.

7.2.2.1 Coal combustion

Fossil fuels such as coal contain naturally occurring radioactivity from uranium, thorium, radium, and their daughter products. The combustion of coal as a fossil fuel for electric power and industrial applications results in the generation of ash, which is collected at the bottom of power-plant boilers and in exhaust-stack filters. Consisting mostly of aluminum, iron, calcium, and silicon, coal ash is retained either as bottom ash and boiler slag or as fly ash trapped in exhaust-stack filtration devices. Most of the waste is generated as fly ash, which is entrained with the hot flue gases of the combustion process. The remainder of the ash is heavier and settles to the bottom of the boiler to form what is referred to as bottom ash. Liquid boiler slag is formed when some of the bottom ash melts under the intense heat.[13] Table 7.6 (based on ref. 13) gives a breakdown of the radionuclide concentrations found in NORM wastes from coal combustion. These concentrations, however, can vary widely depending on the mineral content of the coal which, in turn, can vary with mining location and region of the country.

7.2.2.2 Geothermal energy production

Geothermal energy is heat produced and stored in the earth. This energy can be economically extracted from high-temperature crustal rocks, sediments, volcanic deposits, water, steam, and other gases found at accessible depths from the earth's surface. Concentrations of NORM are found in the solid wastes generated by the exploration and development of geothermal systems and the extraction of the earth's geothermal energy for use in either producing electric power or supplying direct heat. These NORM wastes include minerals that precipitate out of solution and form scale or sludge on the inside surfaces of the drilling and production equipment (e.g., steam turbines, heat exchangers, process lines, valves, turbines, and fluid-handling equipment) used to extract geothermal heat. Such wastes contain barium, calcium, and strontium salts (carbonates, sulfates, and silicates) and silica as well as significant concentrations of radium and radium decay products. Radium is slightly soluble and, consequently, can be brought to the surface and coprecipitated with barium and calcium salts onto the inside surfaces of drilling and production equipment. The principal wastes of concern are the scales in piping and production equipment and the filter cake produced from treatment of spent geothermal fluids prior to their reinjection. Scales are hard, insoluble sulfate deposits that form on the inside of pipes, tubulars, filters, pumps, well heads, and other water-handling equipment.[12] Concentrations of NORM in geothermal wastes will vary with the geology and mineralogy of a geothermal resource area along with the physical and chemical changes that occur during energy extraction.[13] Table 7.7 (based on ref. 13) gives a breakdown of typical radionuclide concentrations found in NORM wastes from geothermal energy production.

7.2.2.3 Metal mining and processing

The mining and processing of metal ores, other than uranium and phosphate, generates large quantities of NORM wastes. These wastes include ore tailings and smelter slag, some of which contain elevated concentrations of uranium, thorium, radium, and their decay products that were originally part of the process feed ore. The extraction process for some ores can yield a waste product (e.g., tailings or slag) that has a higher radionuclide concentration than the original ore. Tailings are the solid materials remaining after physical or chemical benefication (washing, flotation, grinding, and drying) removes the valuable metal constituents from the ore. Slag is the vitreous residue mass left from the smelting (blast furnace melting and conversion) of metal ore for extraction and purification.[13]

The EPA study (ref. 13) describes NORM wastes from the mining and processing of three categories of metals: rare earth metals, special application metals, and metals produced in bulk quantities (i.e., large volumes) by industrial extraction processes. Rare earth (or lanthanide) metals comprise 16 chemical elements, including those with atomic numbers 57 (lanthanum) through 71 (lutetium) as well as yttrium (atomic number 39), which has similar chemical properties. Special application metals are regarded as metals that have unique commercial and industrial uses and include hafnium, tin, titanium, and zirconium. Metals mined and processed in bulk for industrial applications include aluminum, copper, iron, lead, zinc, and precious metals like gold and silver.[13]

The level of NORM found in metal ores depends more on the geologic formation or region than on the particular mineral being mined. Table 7.8 (based on ref. 13) gives a breakdown of typical radionuclide concentrations found in NORM wastes from each of the three categories of mined metals.[13]

7.2.2.4 Municipal water treatment

A small portion of the public water supply systems in the United States treat water containing elevated NORM radionuclide concentrations—most significantly, uranium and radium. Radionuclides are leached into ground or surface water when the water comes in contact with uranium- and thorium-bearing geologic media. The predominant radionuclides found in water include those of uranium, radium, radon, and their decay products. Many water-treatment technologies typically used for removing solids from water for softening and purification can significantly reduce the level of NORM radioactivity. NORM wastes from municipal water treatment consist of radioactive-contaminated sludges and solids that include filter sludges, spent ion-exchange resins, spent granular activated carbon, and water from filter backwash. Radium-selective ion-exchange resins generate wastes at much higher concentrations than do those found in sludge, but in smaller quantities. In fact, some of these wastes fall into the discrete NARM waste category because their concentrations exceed 2 nCi/g.[13] Table 7.9 (based on ref. 13) gives estimated typical radionuclide concentrations of NORM wastes from municipal water treatment. These concentrations can vary significantly from location to location because of the varying geologic characteristics of different water sources in different regions of the country.

7.2.2.5 Oil and natural gas production and processing

Some oil and natural gas production and processing activities generate NORM wastes. Radium is a major contributor to the radioactivity found in these wastes, which are found in pipe scale and sludge from production and processing operations. Uranium and thorium compounds are mostly insoluble, and as oil and natural gas are brought to the surface, these compounds tend to remain embedded in underground geologic formations. However, some radium and radium daughter products are slightly soluble in water and can become mobilized when ground water (containing dissolved mineral salts) is brought to the surface from production and processing. When this occurs, some radium and its daughters may precipitate out of solution because of geologic chemical changes and reduced temperature and pressure. Radium concentrations from geologic formations can precipitate out in sludges and on the internal surfaces of oil and natural gas piping and production and processing equipment. The solid scale residue typically consists mainly of barium, calcium, and strontium sulfates, silicates, and carbonates along with smaller portions of radium compounds. Sludge deposits, consisting of barium and silica compounds, are generally in the form of oily, loose material. NORM radionuclide concentrations in scales that accumulate in process piping and surface equipment may vary from background soil levels (about 1 pCi/g) to several hundred thousand picocuries per gram—with an average activity of about 1000–2000 pCi/g.[16] Concentrations in sludges range from background levels to several hundred picocuries per gram. Radium and its decay products are also found in elevated concentrations in ground water extracted to the surface from oil drilling. However, these concentrations are much less than those found for the scale or sludge wastes.[13]

NORM wastes from natural gas plant deposits differ from oil production NORM wastes and typically consist of radon decay products plated out on the interior surfaces of pipes, valves, filters, and other gas production and processing equipment.[13]

Table 7.10 (based on ref. 13) gives estimated radionuclide concentrations of NORM wastes from both oil and natural gas production and processing. As with other NORM wastes, the radioactivity concentrations for the scale and sludge wastes are strongly influenced by the natural abundance of radionuclides, the geologic formation conditions where the oil and natural gas are produced, and the characteristics of the production process.[13,17]

7.2.2.6 Phosphate mining and fertilizer production

NORM wastes are generated from the mining and processing of phosphate rock (phosphorite) needed to produce phosphate fertilizers, detergents, animal feed, food products, pesticides, and other phosphorous chemicals. These wastes include ferrophosphorus, phosphogypsum (a hydrated calcium sulfate slurry), piping scale, and slag (calcium silicate).[13]

Phosphogypsum and scale are the principal waste by-products generated during the production of phosphoric acid and fertilizers. Scale is deposited in small quantities in process piping and in filtration receiving tanks. Phosphate scale wastes are generally regarded as discrete NORM because ^{226}Ra concentrations in small volumes of these materials have been found be as high as 100,000 pCi/g.[13,18]

Ferrophosphorus and phosphate slag are the principal waste by-products from the production of elemental phosphorous, which is produced by the reduction of phosphate rock in large electric furnaces that use carbon and silica as catalysts. Both ferrophosphorus and slag are found in the residual solids that remain from the furnace processing.[13]

Table 7.11 (based on ref. 13) gives estimated radionuclide concentrations in the principal NORM wastes from phosphate mining and fertilizer production. These concentrations include contributions from uranium, thorium, radium, and their radioactive decay products, which are found in mined phosphate ores and have become concentrated in the waste by-products. Actual radionuclide concentrations will vary in location because of varying geological characteristics of phosphate ores in different regions of the country as well as variations in the processes used for phosphate mining and production.[13]

7.3 GENERATION, INVENTORIES AND PROJECTIONS

Limited information is available on the generation, inventories, and projections of domestic NARM wastes. Table 7.12 reports the inventories of radium disposed of in recent years by New York State generators.[10] Currently, NARM wastes are shipped for disposal to either the Envirocare Facility near Clive, Utah, or the U.S. Ecology, Inc., site near Richland, Washington. As Table 0.8 in Chapter 0 shows, nearly 297,000 m^3 of NARM wastes were disposed of at the Envirocare Facility by the end of FY 1996. Most of these wastes were generated from programs sponsored by DOD and EPA. Only a small portion (4.5%) of the cumulative volume of NARM wastes disposed of at the Envirocare Facility resulted from commercial activities.

Like inventories, projections of NARM (and NORM) are limited and vary according to the region of the country. Table 7.13 (adapted from refs. 13 and 15) reports a summary of estimates of domestic diffuse NORM waste generation, material density, cumulative inventory, and radioactive (^{226}Ra) concentration. These estimates are reported in refs. 13 and 15 and pertain to wastes from commercial rather than DOE activities. EPA information and data reported from ref. 13 are, in turn, based on refs. 17–30. It should be cautioned that the large quantities reported in Table 7.13 for total NORM inventories are preliminary estimates associated with large ranges of uncertainty. These estimates do not indicate how much of these materials would actually be managed and disposed of as radioactive waste. Consequently, caution should be used in trying to extrapolate any of the referenced information and data for purposes such as risk assessment or determining needed disposal facilities. The estimates given in Table 7.13 also do not reflect possible opportunities for the reuse and recycling of NORM materials in commercial and industrial applications. Such applications are further discussed in ref. 13.

The ubiquitous nature of NORM wastes accounts for the apparent enormous inventory of these materials. Even allowing for uncertainties, the estimated cumulative volume of these materials is much larger than the cumulative volume of DOE and commercial radioactive waste and SNF being managed through CY 1996 (see the tables of Chapter 0 and Chapter 6).

The total inventory that should be associated with NORM will depend on what regulatory concentration standards can be applied to these materials on a national basis. Future updates of this document will include additional and updated information and data on both accelerator-produced waste and NORM waste inventories, projections, and characteristics as they become available.

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Table 7.1. Current status of state NORM regulations[a]

Status description	List of states
States that currently either have NORM regulations in place or a set of regulations drafted	Alabama, Alaska, Arkansas, Georgia, Hawaii, Illinois, Kansas, Kentucky, Louisiana, Michigan, Mississippi, New Mexico, Ohio, Oklahoma, Texas
States that have NORM regulations in preparation or anticipated	Colorado, Connecticut, New Jersey, Washington
States awaiting CRCPD[b] guidelines for NORM	California, North Dakota, Oregon
States who feel that their NORM wastes are covered adequately by existing regulations	Delaware, Idaho, Maine, Maryland, Massachusetts, Minnesota, Nebraska, Nevada, New Hampshire, New York, Rhode Island, South Carolina, Utah, Vermont, Virginia, West Virginia, Wisconsin
States that have no current action plans for NORM	Arizona, Florida, Indiana, Iowa, Missouri, Montana, North Carolina, Pennsylvania, South Dakota, Tennessee, Wyoming

[a]As of the end of February 1997. Based on refs. 3 and 4.
[b]Conference of Radiation Control Program Directors.

Table 7.2. Radionuclides found in accelerator-produced radioactive materials[a]

Nuclide	Atomic number	Half-life[b]	Principal mode(s) of decay[c]	Nuclide	Atomic number	Half-life[b]	Principal mode(s) of decay[c]
^{11}C	6	20.4 min	β^+	^{81}Rb	37	4.6 h	EC
^{13}N	7	10.0 min	β^+	^{82}Rb	37	6.4 h	β^+, γ
^{15}O	8	2.0 min	β^+	^{84}Rb	37	34.0 d	EC
^{18}F	9	1.8 h	β^+	^{82}Sr	38	25.0 d	EC
^{22}Na	11	2.6 y	β^+, γ	^{87m}Sr	38	2.8 h	IT
^{28}Mg	12	21.1 h	β, γ	^{87}Y	39	80.3 h	EC
^{28}Al	13	2.2 min	β, γ	^{97m}Tc	43	90.0 d	IT
^{33}P	15	25.3 d	β	^{111}In	49	2.83 d	EC, γ
^{37}Ar	17	34.8 d	EC	^{123}I	53	13.1 h	EC, γ
^{43}K	19	22.2 h	β, γ	^{124}I	53	4.2 d	EC, γ
^{49}Sc	21	57.3 min	β, γ	^{125}I	53	59.7 d	EC, γ
^{52}Mn	25	5.7 d	β^+, γ	^{126}I	53	13.0 d	EC, γ
^{52}Fe	26	8.3 h	β^+, γ	^{127}Xe	54	36.4 d	EC, γ
^{57}Co	27	271 d	EC	^{131}Cs	55	9.7 d	EC
^{58}Co	27	71 d	EC	^{145}Pm	61	18 y	EC
^{62}Cu	29	9.8 min	β^+, γ	^{157}Dy	66	8.1 h	EC, γ
^{67}Cu	29	61.7 h	β, γ	^{190}Os	76	9.9 min	IT
^{62}Zn	30	9.2 h	EC, γ	^{190}Ir	77	12.2 d	EC, γ
^{66}Ga	31	9.5 h	β^+, γ	^{190m}Ir	77	1.2 h	IT
^{68}Ge	32	287 d	EC, γ	^{193m}Pt	78	4.3 d	IT
^{73}As	33	80.3 d	EC	^{195}Au	79	184.0 d	EC, γ
^{73}Se	34	7.1 h	β^+	^{197}Hg	80	64.1 h	EC, γ
^{77}Br	35	56.0 h	β^+, γ	^{199}Tl	81	7.4 h	EC, γ
^{77}Kr	36	1.2 h	β^+	^{203}Pb	82	52.1 h	EC, γ
^{81}Kr	36	2.1E+05 y	EC	^{204}Bi	83	11.3 h	EC, γ

[a]Based on ref. 7.

[b]y = years, d = days, h = hours, and min = minutes.

[c]α = alpha decay, β = negative beta decay, β^+ = positive beta decay, γ = gamma emission, EC = electron capture, and IT = isomeric transition.

Table 7.3. Characteristics of naturally occurring radionuclides present in the Earth's crust and in associated fluids and gases[a]

Radionuclide	Atomic number	Half-life[b]	Principal mode(s) of decay[c]
^{3}H	1	12.33 y	β
^{7}Be	4	53.28 d	EC, γ
^{14}C	6	5730 y	β
^{40}K	19	1.277E+09 y	β (89%), EC (11%), γ
^{50}V	23	1.4E+17 y	β (30%), EC (70%), γ
^{87}Rb	37	4.88E+10 y	β
^{113}Cd	48	9.3E+15 y	β
^{115}In	49	4.4E+14 y	β
^{123}Te	52	>1.3E+13 y	EC
^{138}La	57	1.05E+11 y	β (30%), EC (70%)
^{144}Nd	60	2.38E+15 y	α
^{147}Sm	62	1.06E+11 y	α
^{148}Sm	62	7E+15 y	α
^{152}Gd	64	1.1E+14 y	α
^{176}Lu	71	3.78E+10 y	β, γ
^{174}Hf	72	2.0E+15 y	α
^{180}Ta	73	>1.2E+15 y	EC, $β^+$, γ
^{187}Re	75	4.6E+10 y	β
^{186}Os	76	2E+15 y	α
^{190}Pt	78	6.5E+11 y	α
^{215}Bi	83	7.6 min	β, γ
^{215}At	85	1.0E−04 s	α, γ
^{218}At	85	1.5 s	α, β
^{219}At	85	56 s	α, β
^{232}Th[d]	90	1.405E+10 y	α
^{235}U[d]	92	7.037E+08 y	α
^{238}U[d]	92	4.468E+09 y	α

[a]Based on ref. 8.

[b]y = years, d = days, h = hours, min = minutes, and s = seconds.

[c]α = alpha decay, β = negative beta decay, $β^+$ = positive beta decay, γ = gamma emission, EC = electron capture, and IT = —isomeric transition.

[d]Also includes other radionuclides in its decay chain series (see Table A.5 of Appendix A).

Table 7.4. Domestic processes that generate NORM waste[a]

Process	Waste generated	Classification by specific activity[b]	Major generator locations(s)
Coal combustion	Fly ash Bottom ash and slag	Diffuse Diffuse	Midwestern and South Atlantic states
Geothermal energy production	Solid wastes	Diffuse	California
Manufacturing	Old/used products: industrial gauges, radium watches and industrial dials, and radium needles in medical equipment	Discrete	Various commercial sites
Metal mining and processing	Slag, leachate, and tailings from the following:		
	Rare earth metals	Diffuse	California, Florida, and North Carolina
	Special-application metals (zirconium, hafnium, titanium, and tin)	Diffuse	Ohio, Delaware, and Florida
	Large-volume metal-processing industries (copper, iron, etc.)	Diffuse	Ohio, Pennsylvania, Indiana, Illinois, Michigan, and some western states
Municipal water treatment	Sludge Radium selective resins	Diffuse Discrete	North central (e.g., Illinois) and coastal plain (e.g., North Carolina) states and other states
Oil and natural gas production and processing	Scale Sludge Contaminated water and production/processing equipment	Discrete or diffuse Diffuse Diffuse	In all petroleum and natural gas states having production and processing facilities[c]
Phosphate mining and fertilizer production	Ferrophosphorous Phosphogypsum[d] Scale Slag	Diffuse Diffuse Discrete Diffuse	Florida, Idaho, and other states in the West and Southeast

[a]Based on ref. 10 (p. 13–9), and refs. 11 and 12.

[b]In fact, many of the wastes generated can be either diffuse or discrete. What is listed in this column is the classification most typically associated with a particular waste generated.

[c]As yet, the geographic distribution of NORM from oil and natural gas production and processing has not been well characterized statistically.

[d]Calcium sulfate.

Table 7.5. Major radionuclides found in diffuse NORM wastes[a]

Nuclide	Atomic number	Half-life[b]	Principal mode(s) of decay[c]	Natural decay series[d]	Principal source(s)[e]
^{238}U	92	4.468E+09 y	α	U	1, 2, 4, 5, 7
^{235}U	92	7.037E+08 y	α	A	1, 5, 7
^{234}U	92	2.454E+05 y	α	U	1, 2, 4, 5, 7
^{231}Pa	91	3.276E+04 y	α	A	1, 5
^{232}Th	90	1.405E+10 y	α	T	1, 5, 7
^{230}Th	90	7.54E+04 y	α	U	1, 2, 4, 5, 7
^{228}Th	90	1.913 y	α	T	1, 5, 6, 7
^{227}Ac	89	2.177E+01 y	β	A	1, 5
^{228}Ra	88	5.75 y	β	T	1, 5, 6
^{226}Ra	88	1.600E+03 y	α	U	1, 2, 3, 4, 5, 6, 7
^{224}Ra	88	3.66 d	α	T	1, 5, 6, 7
^{222}Rn	86	3.825 d	α	U	1, 2, 3, 4, 5, 6, 7
^{210}Po	84	1.383E+02 d	α	U	1, 2, 4, 5, 6, 7
^{210}Pb	82	1.94E+01 y	β	U	1, 2, 4, 5, 6, 7
^{40}K	19	1.277E+09 y	β		1, 2, 4, 6, 7

[a]Based on refs. 13 and 15.
[b]y = years and d = days.
[c]α = alpha decay and β = negative beta decay.
[d]U = uranium series (^{238}U parent, ^{206}Pb stable end daughter); A = actinium series (^{235}U parent, ^{207}Pb stable end daughter); and T = thorium series (^{232}Th parent, ^{208}Pb stable end daughter).
[e]1 = coal combustion; 2 = geothermal energy production; 3 = manufacturing (industrial gauges, watches, etc., and medical needles); 4 = metal mining and processing; 5 = municipal water treatment; 6 = oil and gas production; and 7 = phosphate mining and fertilizer production.

Table 7.6. Radionuclide concentrations in coal combustion wastes[a]

Nuclide	Concentration (pCi/g)	
	Fly ash	Bottom ash and slag
^{238}U	2.6	0.7
^{235}U	0.13	0.03
^{234}U	2.6	0.7
^{231}Pa	0.13	0.03
^{232}Th	1.7	0.4
^{230}Th	1.8	0.5
^{228}Th	2.6	0.6
^{227}Ac	0.13	0.03
^{228}Ra	1.4	0.4
^{226}Ra	3.0	0.7
^{210}Po	5.6	1.4
^{210}Pb	5.4	1.4
Total[b]	27.1	6.9

[a]Based on ref. 13, which assumes that 80 wt % of the concentration is fly ash.

[b]Excludes contributions from other (short-lived) radionuclides in decay chains.

Table 7.7. Radionuclide concentrations in geothermal energy production waste[a]

Nuclide	Waste concentration (pCi/g)
^{228}Th	25
^{228}Ra	93
^{226}Ra	132
^{210}Po	96
^{210}Pb	96
Total[b]	442

[a]Based on ref. 13.
[b]Excludes contributions from other (short-lived) radionuclides in decay chains.

Table 7.8. Radionuclide concentrations in metal mining and processing wastes[a]

Nuclide	Waste concentration, pCi/g		
	Rare earth metals	Special-application metals	Large-volume industry metals
^{238}U	900	43	10.0
^{235}U	45	2.2	0.5
^{234}U	900	43	10.0
^{231}Pa	45	2.2	0.5
^{232}Th	2,000	22	10.0
^{230}Th	900	43	10.0
^{228}Th	2,000	22	10.0
^{227}Ac	45	2.2	0.5
^{228}Ra	2,000	22	10.0
^{226}Ra	900	43	5.0
^{210}Po	630	30	3.5
^{210}Pb	630	30	3.5
Total[b]	10,995	305	73.5

[a]Based on ref. 13.

[b]Excludes contributions from other (short-lived) radionuclides in decay chains.

Table 7.9. Radionuclide concentrations in municipal water treatment wastes[a]

Nuclide	Concentration (pCi/g)	
	Sludges	Radium selective resins
^{238}U	4.0	b
^{235}U	0.03	b
^{234}U	4.0	b
^{231}Pa	0.03	b
^{232}Th	0.2	b
^{230}Th	0.2	b
^{228}Th	9.0[c]	b
^{227}Ac	0.03	b
^{228}Ra	16[c]	b
^{226}Ra	16	35,000[d]
^{210}Po	11.0	b
^{210}Pb	11.0	b
Total[e]	71.5	b

[a]Based on ref. 13.
[b]Unknown.
[c]Concentration after 2 years of decay and ingrowth.
[d]Rough estimate.
[e]Excludes contributions from other (short-lived) radionuclides in decay chains.

Table 7.10. Radionuclide concentrations in oil and natural gas production and processing wastes[a]

Nuclide	Concentration (pCi/g)	
	Scale	Sludge
^{228}Th	120	19
^{228}Ra	120	19
^{226}Ra	360	56
^{210}Po	360	56
^{210}Pb	360	56
Total[b]	1,320	206

[a]Based on ref. 13.

[b]Excludes contributions from other (short-lived) radionuclides in decay chains.

Table 7.11. Radionuclide concentrations in phosphate wastes[a]

Nuclide	Concentration (pCi/g)			
	Ferrophosphorous	Phosphogypsum	Scale	Slag
^{238}U	b	6.0	b	25
^{235}U	b	0.3	b	1.3
^{234}U	b	6.2	b	24
^{231}Pa	b	0.3	b	1.3
^{232}Th	b	0.27	b	0.77
^{230}Th	b	13	b	32
^{228}Th	b	1.4	b	0.77
^{227}Ac	b	0.3	b	1.3
^{228}Ra	b	0.27	b	0.77
^{226}Ra	1.2[c]	33	1000[d]	35
^{210}Po	b	26	b	35
^{210}Pb	b	26	b	35
Total[e]	b	113	b	192

[a]Based on ref. 13.
[b]Unknown.
[c]Average for Florida plants.
[d]Rough estimate for purposes of illustration and comparison.
[e]Excludes contributions from other (short-lived) radionuclides in decay chains.

Table 7.12. Quantities of radium disposed of by New York State generators during 1987–91[a]

CY	Volume (m^3)	Radioactivity (Ci)
1987	16.1	1.32
1988	4.0	4.23
1989	26.7	123
1990	6.4	0.08
1991	6.7	1.28
Totals	59.9	129.91

[a]Based on ref. 10 (p. 13–9).

Table 7.13. Estimates of domestic diffuse NORM waste generation, material density, total inventory, and radioactive concentration[a]

Process/waste material	Current annual generation (10^6 t/year)	Waste material density (t/m^3)	Total inventory: Mass (10^6 t)	Total inventory: Volume[b] (10^6 m^3)	Total inventory: Radioactivity[c] (Ci)	Average ^{226}Ra concentration (pCi/g)
Coal combustion						
Bottom ash and slag	17	(1.50)[d]	>337[e]	>225	2,300	(3.1)
Fly ash	44	1.20	>959[e]	>800	26,000	(3.9)
Geothermal energy production (scale and filter cake)	0.054	1.80	0.74	0.41	330	132
Metal mining and processing—slag leachate, and tailings from the following:						
• Large bulk metal industries (e.g., aluminum, copper, iron, and steel)	1,000	2.00	50,000[f]	25,000	3,700,000	(5)
• Rare earths	0.021	2.00	1[f]	0.5	11,000	900
• Special-application metals (zirconium, hafnium, titanium, and tin)	0.47	2.00	20[f]	10	6,100	43
Municipal water treatment						
Radium selective resins	0.04	(1.50)	2[g]	>1	>35,000	(35,000)
Sludges	0.26	1.60	10[g]	6	700	16
Oil and gas production waste (scale and sludge)[h]	0.056	1.70	4	2.3	1,210	84
Phosphate production						
Ferrophosphorous	i	(1.50)	i	i	i	1.2[j]
Phosphogypsum	48	1.44	8,200	5,700	930,000	33
Scale	0.003	(2.00)	<<1	<<1	<1,000	(1,000)
Slag	1.6	1.90	324[k]	171	62,200	35
Total	1,112	1.88[l]	>59,857	>31,917	>4,775,840	9.6[l]

[a]Based on refs. 13 and 15. Information and data from ref. 13 are, in turn, based on refs. 17–30.
[b]Estimated from listed waste material density.
[c]Estimated from total radionuclide concentrations listed in Tables 7.6–7.11. Excludes contributions from ^{40}K.
[d]Data listed in parentheses represent rough estimates developed for illustration and comparison.
[e]Based on cumulative ash production rate from 1966 through 1990. Assumes that 74 wt % of cumulative production is fly ash.
[f]Based on average annual generation applied to a 50-year period.
[g]Based on the average annual generation applied to a 40-year period.
[h]Based on ref. 30.
[i]Unknown.
[j]Average for Florida plants.
[k]Midpoint value in a range based on ref. 29.
[l]Calculated average for all waste materials listed.